Going Nonlinear with Dark Energy

Salman Habib, T-8; Michael S. Warren, Darren Reed, T-6; Katrin Heitmann, ISR-1; Martin White, Lawrence Berkeley National Laboratory

The discovery and confirmation of cosmic acceleration is less than a decade old, yet it is already widely recognized as a harbinger of a revolution in fundamental physics and cosmology. The acceleration could be due to a mysterious dark energy with a peculiar equation of state or it could signal a breakdown of general relativity at very large scales. If the dark energy is literally constant, then its numerical value is ridiculously small compared with theoretical expectations. Although the theoretical existence of this problem has been appreciated since the 1930s, it was widely assumed that a fundamental symmetry was responsible for tuning the cosmological constant exactly to zero. Now, not only do we know this expectation to be false, but we also have to explain its current value–roughly twice that of the energy density in matter in the Universe. Aside from the cosmological constant, there exist dynamical models of dark energy termed quintessence, where the equation of state is time-varying. As long as we do not know whether the dark energy is constant or not, we also do not know what theoretical approach to take to attack the basic puzzle. Thus the very first step is to characterize the equation of state of dark energy as accurately as possible from observations. The challenge posed by next-generation observations has been laid out in the Department of Energy (DOE) Dark Energy Task Force Report [1]. From a theoretical and modeling perspective, the key requirement is a one to two orders-of-magnitude improvement in control of systematic effects.

Cosmological probes of dark energy rely on measuring the expansion history of the Universe and the growth rate of structure formation. For deployment in the near- and medium-term future, four techniques have been put forward. These are baryon acoustic oscillations, and cluster, supernova, and weak lensing cosmological surveys. Of the structure formation-based techniques, both weak lensing and cluster observations can directly measure the growth of structure as well as the expansion history, and hence can test whether general relativity is modified at large scales. The control of systematics in weak lensing is, however, much further advanced than for clusters. The aim of our project is to understand and control the main sources of theoretical errors underlying the baryonic oscillations and weak lensing-based dark energy research program by carrying out large-scale numerical simulations (Fig. 1) to refine and calibrate algorithms and analytic approximations, and potentially serve as templates when the data become available. To support this project, a very significant allocation of institutional computing resources has been made available by LANL.

The source of baryon acoustic oscillations is the tight coupling of the baryon-photon fluid in the early Universe. During this phase, perturbations do not grow but propagate as sound waves. After recombination, the sound waves survive as imprints on the late-time distribution of matter at a scale of 150 Mpc, a fixed "cosmic ruler," which in turn enables accurate measurements of the Hubble parameter and the angular diameter distance. Weak gravitational lensing refers to the distortion of background galaxy images due to the gravitational bending of light rays caused by foreground mass concentrations, the distortion being described in terms of image stretch ("shear") and magnification ("convergence"). Measurements of shear and convergence directly map the distribution of matter in the Universe.

The first global aim of the project is to ensure that the numerical simulations to be carried out can provide a sufficiently complete physical description, yet one that is robust and possesses controlled errors and convergence properties–the hallmark of precision cosmology [2]. The number of simulations, the box sizes used, the initial condition accuracy, and the force and mass resolution needed are all important ingredients in determining the actual suite of simulations that will be performed. A key question is whether enough precision information can be gleaned from a relatively small number of accurate large-scale simulations. Recent investigations by members of the proposing team have made significant progress in this area [3,4]. An example of this approach is shown in Fig. 2. From a small 32-simulation sample, varying five cosmological parameters as well as the cosmological epoch, we can produce prediction results at the 1 percent accuracy at parameter values not included in the original simulation sample.

Another area that has been investigated is the precision of cosmological initial conditions and control of errors in the evolution of the density field on scales relevant to baryonic oscillation observations and weak lensing measurements. Our work has established that subpercent error initial conditions can be implemented and that error control in the evolution can be kept at this level down to length scales of the order of a few Mpc, which is sufficient for the analysis of current and near-term observations. A large suite of cosmological simulations is now being run with the aim of constructing a database for support of cosmological surveys. This database will be used by project members and will be made available to the wider dark energy community in the first half of 2008.

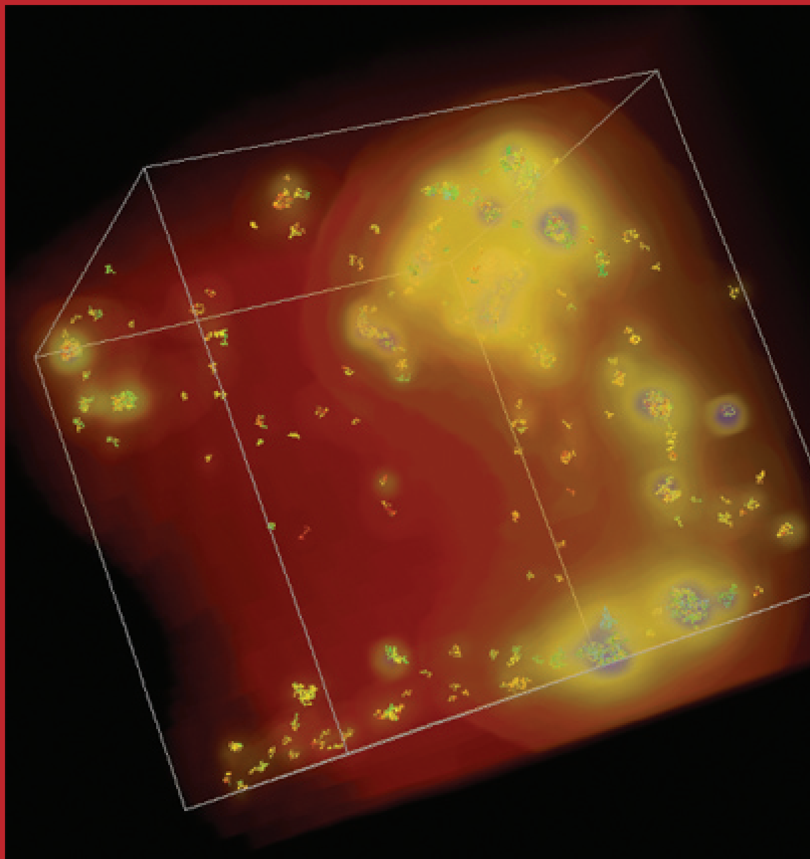

Fig. 1. The density field from a cosmological simulation showing the very large dynamic range in density that needs to be captured to make theoretical predictions for cosmological large-scale structure observations.

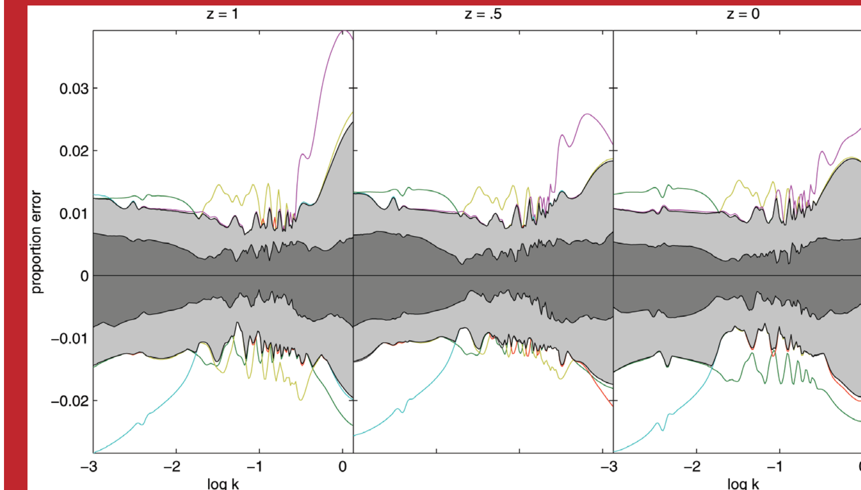

Fig. 2. Holdout error test showing accuracy of power spectrum emulator for weak lensing observations at three redshifts, based on the methodology of [2]. The dark gray zone contains 50 percent of the results, and the light gray, 90 percent. The control on accuracy is at the 1 percent level.

For more information contact Salman Habib at habib@lanl.gov.

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